# Nuclear Power Plant Accidents

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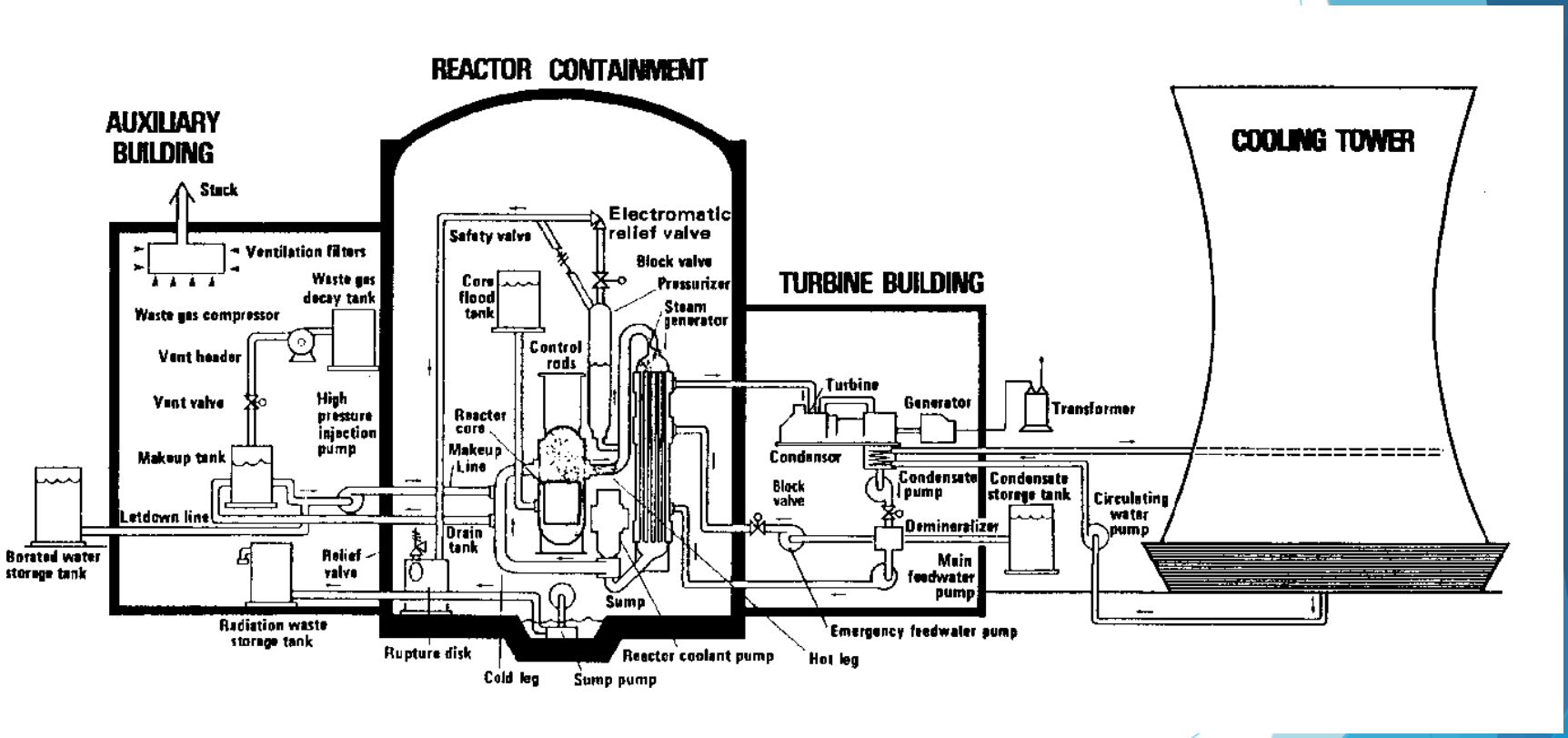
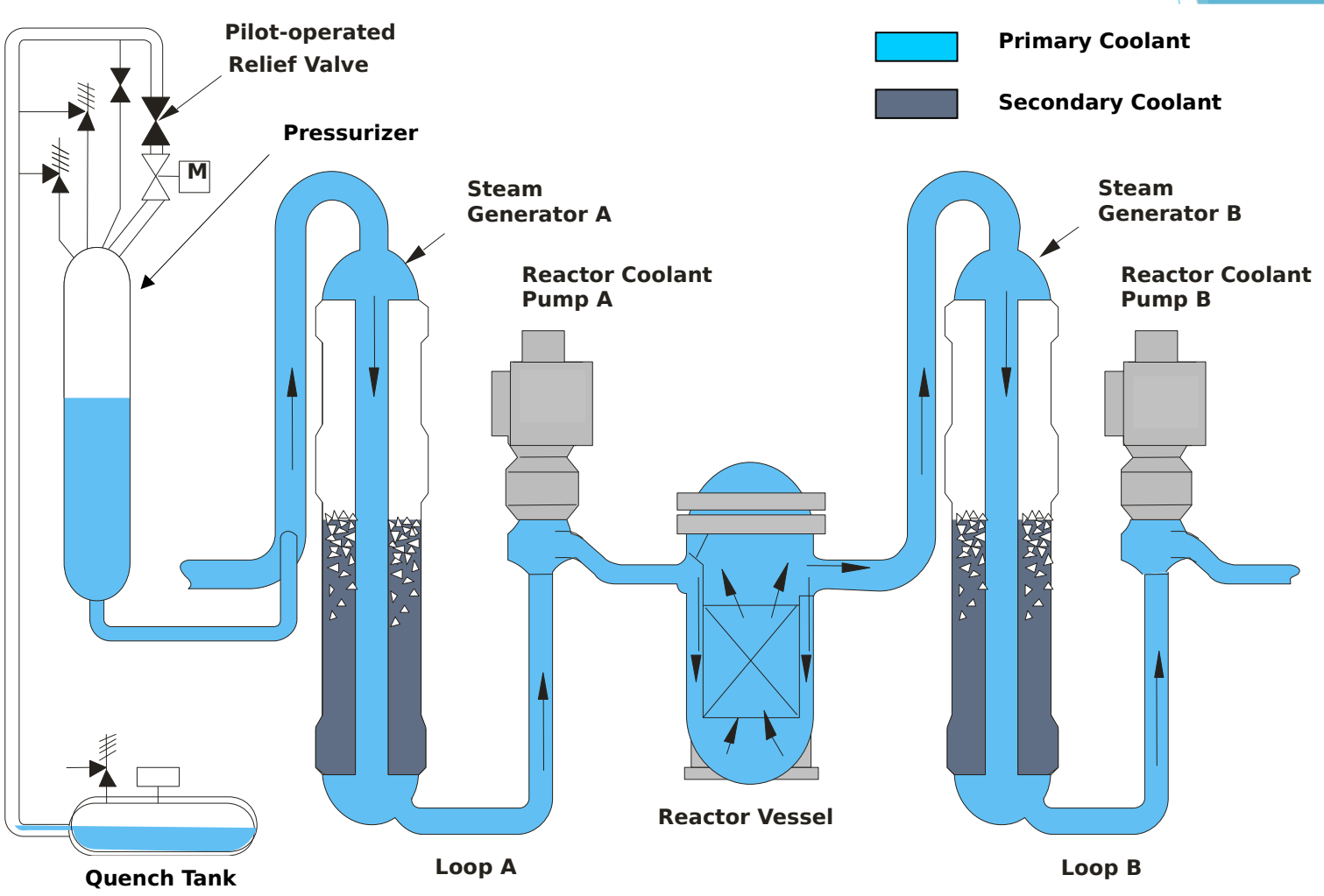
# Three Mile Island Accident

- Date of accident:  March 28, 1979
- Type of nuclear plant:  Babcock & Wilcox 2-loop pressurized water reactor (PWR) with once-through steam generators
- Initiating event:  operational upset in secondary plant (loss of condensate flow) led to trip of main feedwater pumps, which terminated feedwater flow to steam generators causing loss of reactor core heat removal

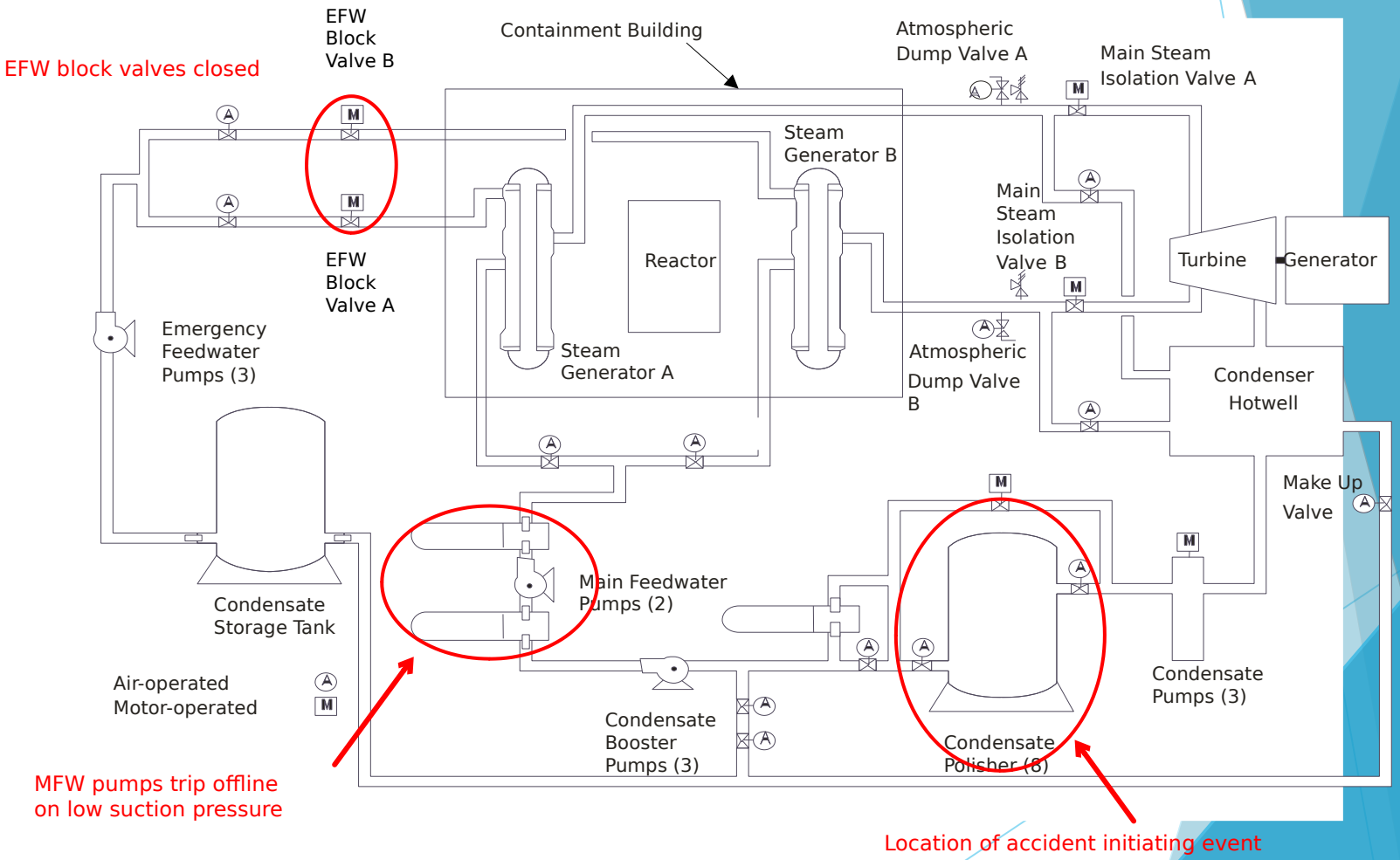
# TMI-2 Reactor Plant Schematic



# TMI Primary Coolant System



# TMI Condensate & Feedwater Systems



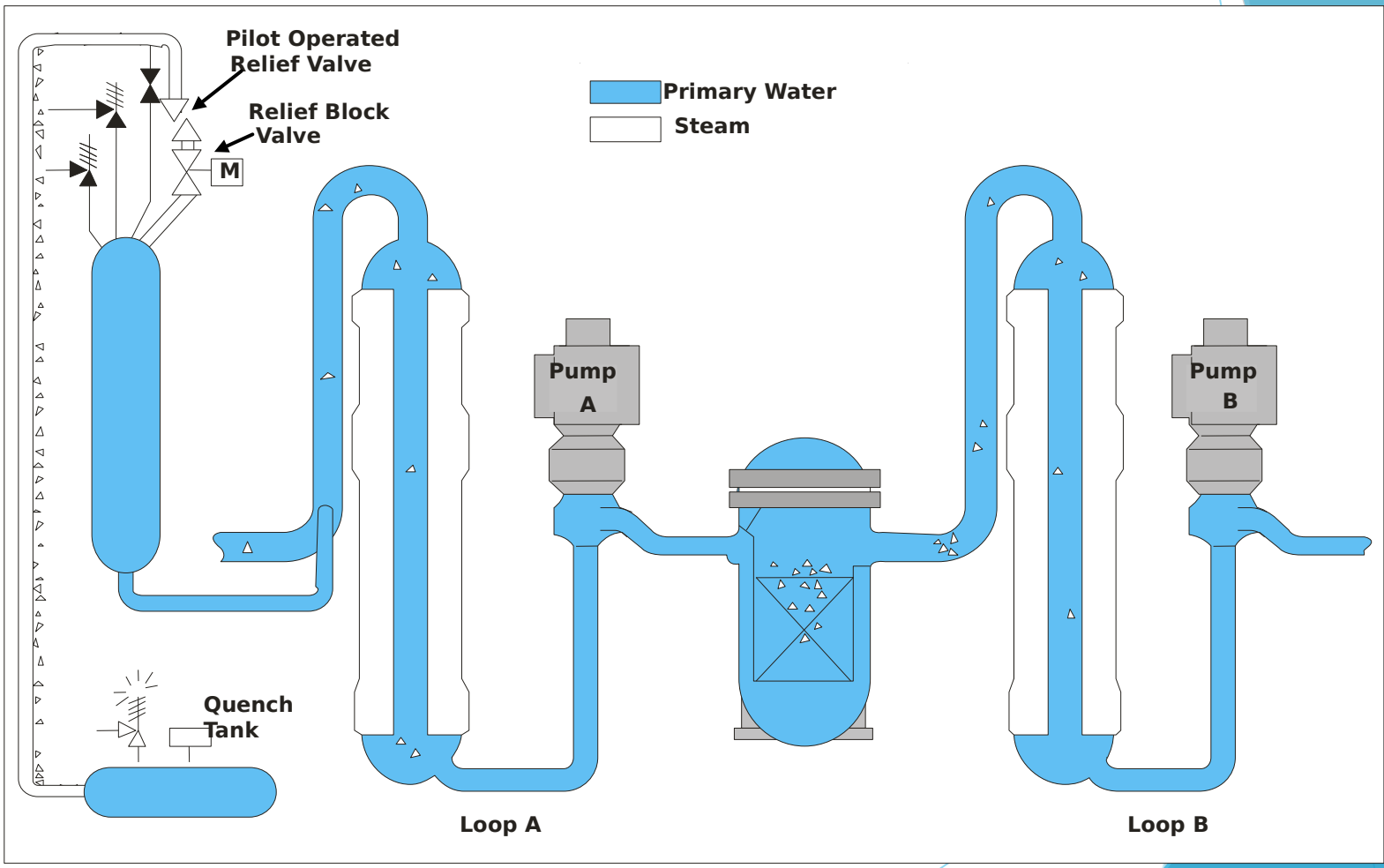
# Three Mile Island Accident (cont.)

- Accident sequence
  - Loss of heat removal from reactor coolant system caused pilot-operated relief valve (PORV) on pressurizer to open as reactor coolant system (RCS) pressure increased
  - Reactor control rods automatically inserted on high RCS pressure, which terminated fission reaction in reactor fuel
  - When RCS pressure dropped below relief valve set-point, PORV failed to close resulting in loss-of-coolant accident (LOCA) condition
  - Steam bubble in pressurizer began rapid reduction in volume (control board light indicated PORV was closed)

# Three Mile Island Accident (cont.)

- Accident sequence (cont.)
  - High-pressure injection (HPI) pumps automatically started pumping water into RCS from borated water storage tank as RCS pressure continued to decrease
  - When pressurizer water level began rising rapidly, HPI throttled in accordance with LOCA procedure to prevent over-pressurizing RCS
  - When system pressure fell below boiling point of water in reactor core steam bubbles began forming
  - Reactor coolant pumps shutdown in response to indications of low system pressure, high vibration, and low coolant flow
  - Steam bubbles exiting reactor core began to collect in reactor vessel head

# TMI Reactor Coolant System 8 Minutes into Accident



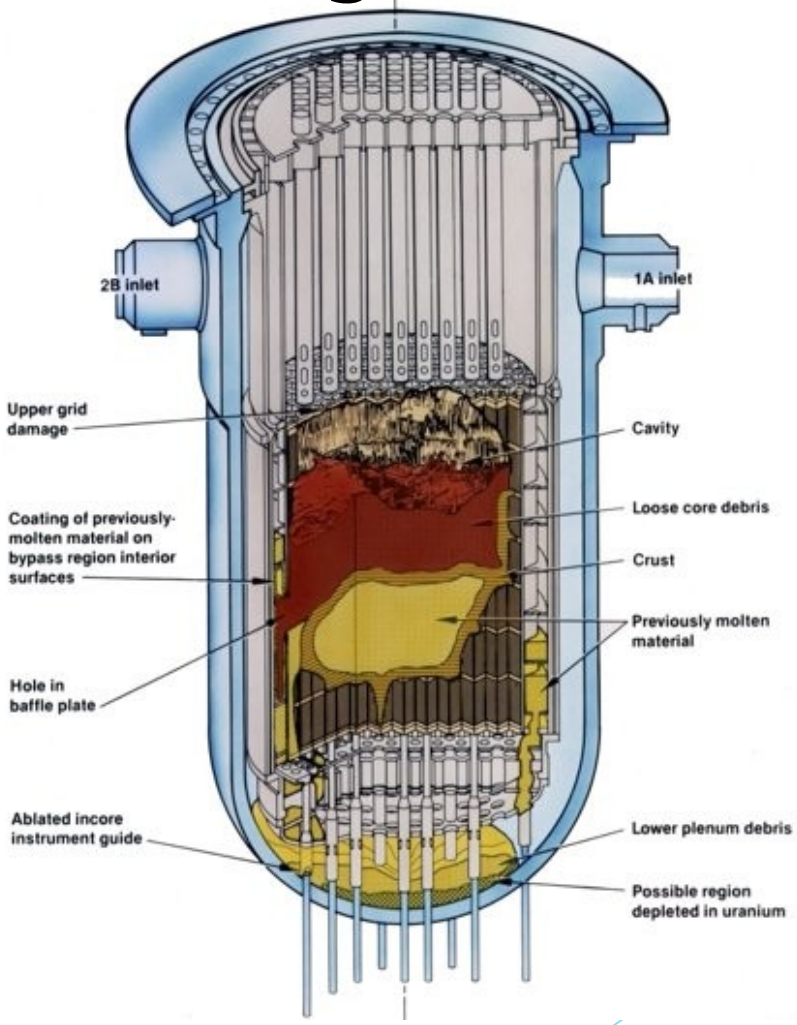
# Three Mile Island Accident (cont.)

- Accident sequence (cont.)
  - Reactor operators, trained in strict adherence to prescriptive operating procedures, overly focused on increasing pressurizer water level instead of on decreasing reactor coolant pressure early in accident
  - Led to subsequent ambiguous control room indications and reactor system conditions that complicated task of mitigating accident while still adhering to operating procedures
    - Control room alarm boards “lit up like a Christmas tree”
    - Computer alarm log printing one line every 4 seconds
  - When finally recognized that PORV was stuck open, PORV block valve closed, terminating loss of reactor coolant

# Three Mile Island Accident (cont.)

- Accident sequence (cont.)
  - Fission product decay heat continued to boil off water in reactor core region until fuel became uncovered and top half of core melted, slumping to bottom of reactor pressure vessel
  - RCS flow restored at about 5 hours into accident, essentially terminating accident
- If reactor coolant system pressure had been criterion for determining continued operation of high-pressure injection system, steam bubble would not have formed in reactor vessel head and fuel melting would not have occurred

# TMI-2 Core End-State Configuration



# Three Mile Island Accident Radiological Consequences

- Only radioactive release from plant was noble gases (krypton and xenon)
- Semi-volatile radionuclides like iodine plated out on reactor coolant system and containment building surfaces
- Max exposure to nearest offsite individual from noble gas release estimated to be no more than 37 mrem (0.37 mSv), or about one-tenth of average American's annual exposure from natural background radiation
- Local population estimated to have received average radiation dose of about 1 millirem above usual annual background dose of 300 mrem

# Three Mile Island Current Plant Status

- Fuel removed from reactor vessel, plant cleaned up, decontaminated, and placed in post-defueling monitored storage
- Unit 2 to be decommissioned with Unit 1 at end of Unit 1’s useful lifetime
- Unit 1 shutdown in September of 2020, but now scheduled for restart to power Microsoft AI data center

# TMI – Pre-Accident

# TMI – Post-Accident

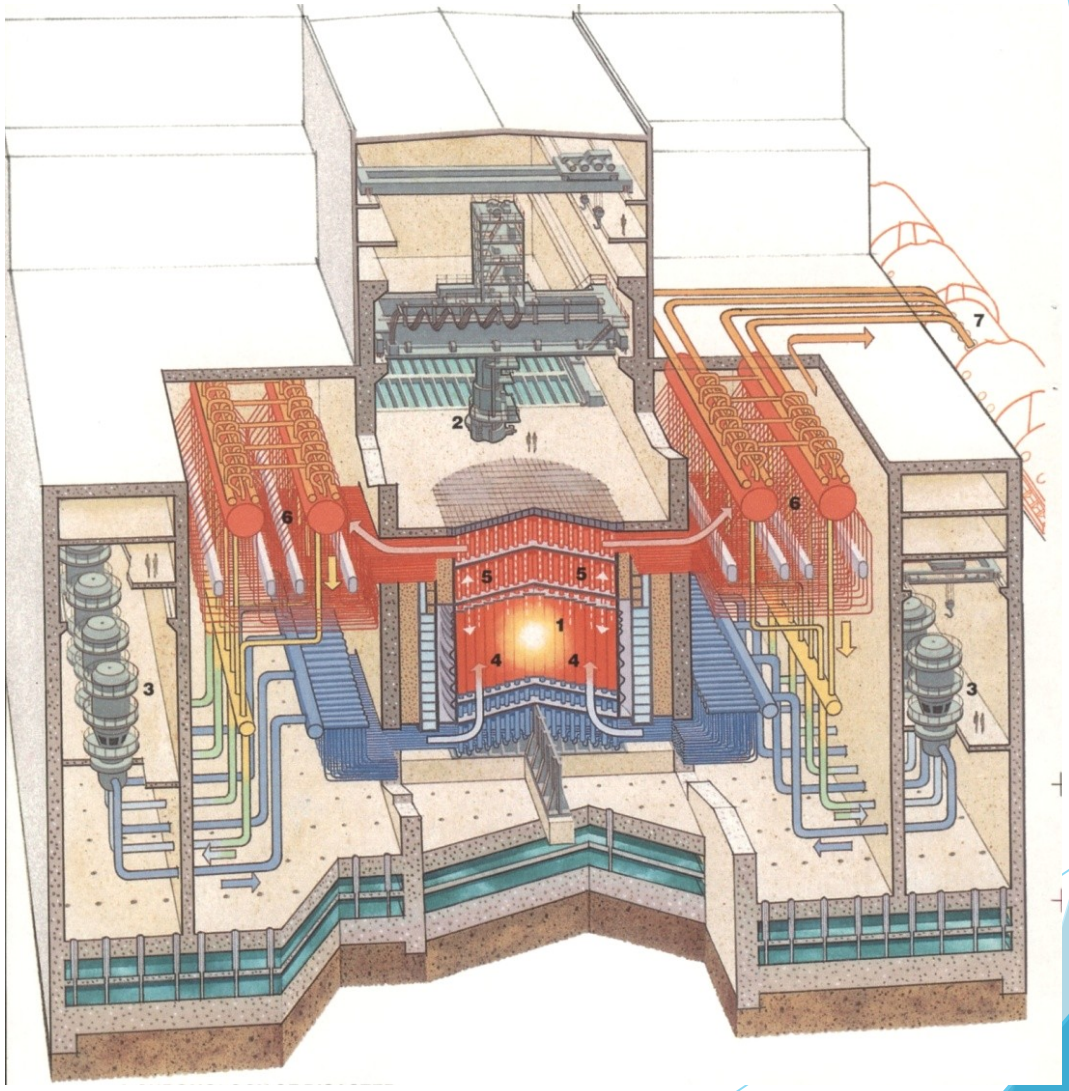
# Industry Changes Resulting from TMI Accident

- Equipment backfits (e.g., system to directly indicate reactor vessel water level)
- Improved man-machine interface (i.e., control room instrumentation, alarms, and layout)
- Procedural changes – symptom-based operating procedures replaced event-based procedures
- Additional plant analyses (i.e., probabilistic risk assessments for all nuclear plants)
- Modifications to operator training, testing, and licensing

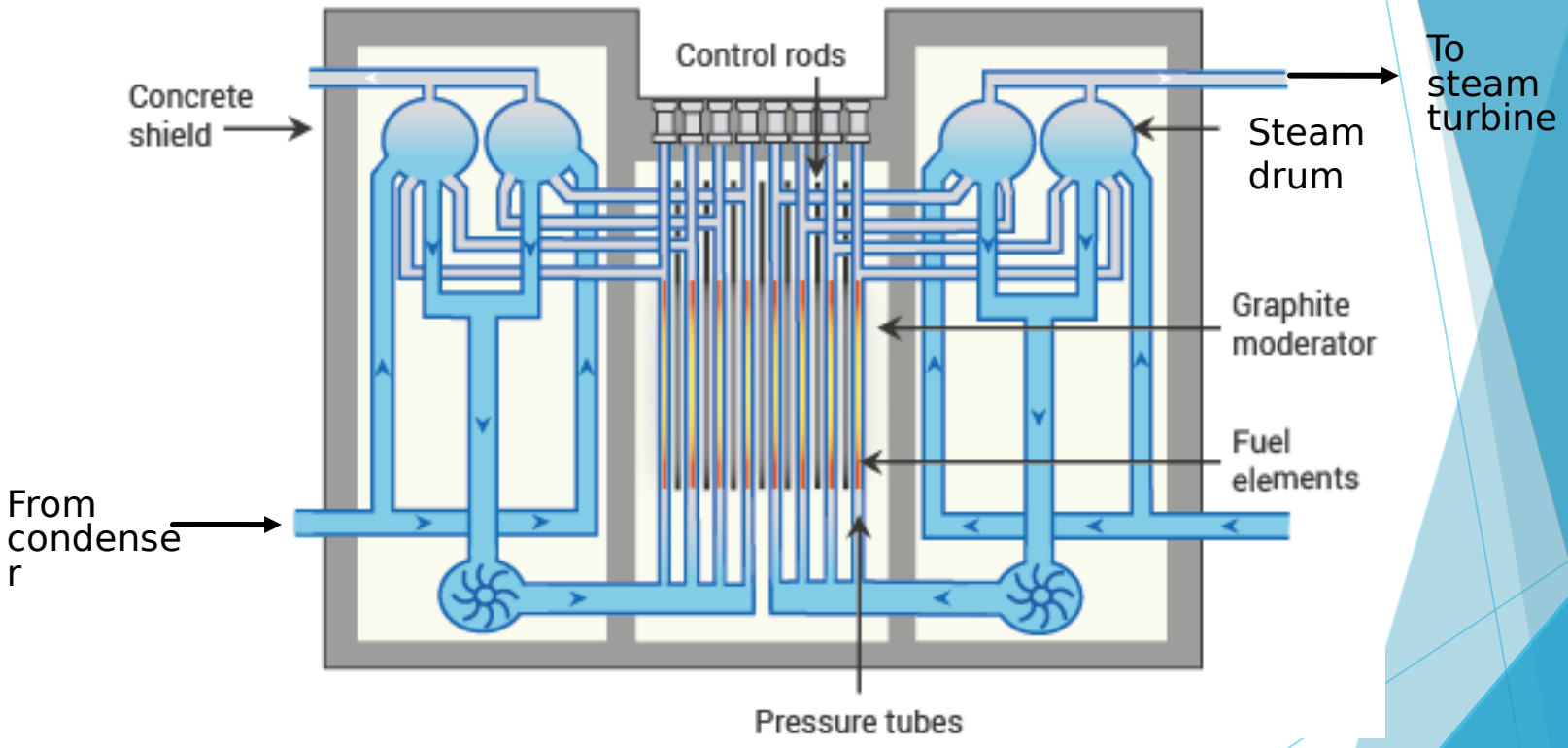
# Chernobyl Accident

- Date of accident:  April 26, 1986
- Type of nuclear plant:  Russian dual–purpose (electricity and plutonium production) pressure-tube graphite reactor with on-line refueling and no containment building
- Initiating event:  performance of a faulty test in which some reactor safety systems were deliberately bypassed; reactivity excursion-caused steam explosion resulted in disruption of nuclear core

# Chernobyl RBMK Reactor



# Chernobyl RBMK Reactor (cont.)



# Chernobyl Accident (cont.)

Accident sequence

- Commencement of test caused rise in reactor power resulting in coolant voiding (localized boiling)
- Positive void reactivity feedback mechanism quickly accelerated power increase
- Operator-initiated control rod insertion too slow to affect rate of power increase
- Uncontrolled power “pulse” caused fuel to disintegrate
- Fragmented fuel contact with water-steam coolant mixture caused steam explosion
- Explosion destroyed reactor building concrete walls and lifted upper biological shield, dispersing burning graphite and nuclear fuel
- Plume of radioactive gases and particulates sent high into atmosphere

# Chernobyl Accident (cont.)

# Chernobyl Nuclear Power Plant Post-Accident

# Chernobyl Unit 4 Destruction

# Chernobyl Accident Radiological Consequences

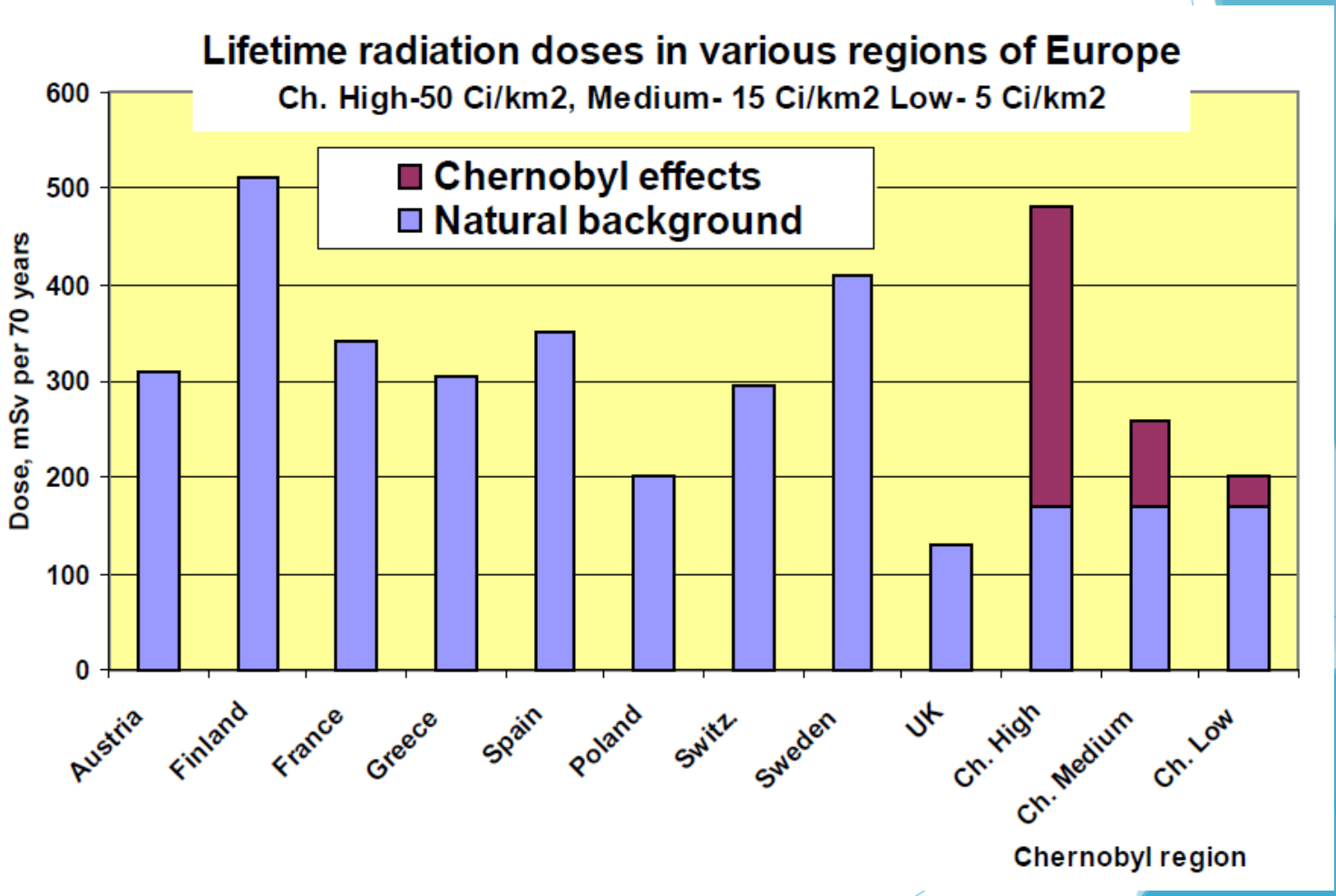
- Radioactive material releases included fission product gases, other volatile elements (e.g., iodine), particulates, aerosols, and graphite-fuel debris from reactor core causing contamination of local countryside
- 32 plant workers and first responders received lethal radiation doses
- More than 200 plant personnel and first responders hospitalized with radiation sickness
- More than 1000 people received “large” radiation doses, but no member of public required hospitalization
- 22 people who recovered from acute radiation exposure died in the following 19 years (only about 6 of these died from cancer)
- Chernobyl workers and populace in 30-km evacuation zone most likely to show detectable increase in long-term health effects, if any

# Fewer Observed Cancers from Chernobyl Radiation Exposures

Dr. Zbigniew Jaworowski, MD PhD DSc, former Chairman of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) stated:

"What is really surprising, however, is that data collected by UNSCEAR and the Chernobyl Forum show **15% to 30% fewer cancer deaths among the Chernobyl emergency workers** and about **5% lower solid cancer incidence** among the people in the Bryansk district (the most contaminated in Russia) in comparison with the general population. In the most irradiated group of these people (mean dose of 40 mSv) the **deficit of cancer incidence was 17%**."

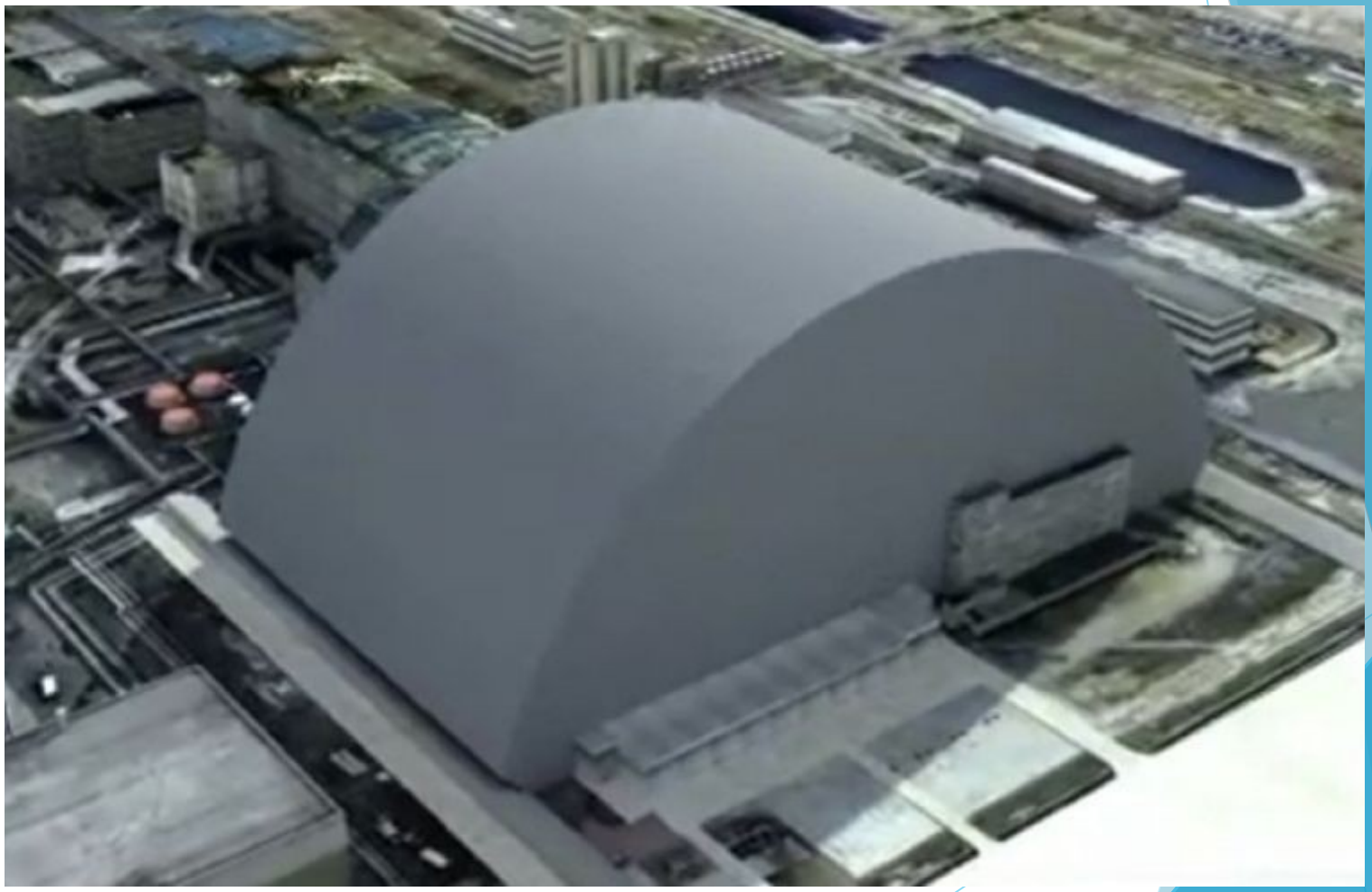
# Chernobyl Accident Radiation Dose Comparisons



# Chernobyl Reactor and Surrounding Area Current Status

- Unit 4 enclosed in permanent confinement structure and continuously monitored for radiation releases
- 15-meter-deep barrier wall constructed to prevent contamination of groundwater
- Local croplands, forests, and orchards decontaminated
- Contaminated soil decontaminated or removed and stored in drums for disposal

# Chernobyl Unit 4 New Safe Confinement Structure



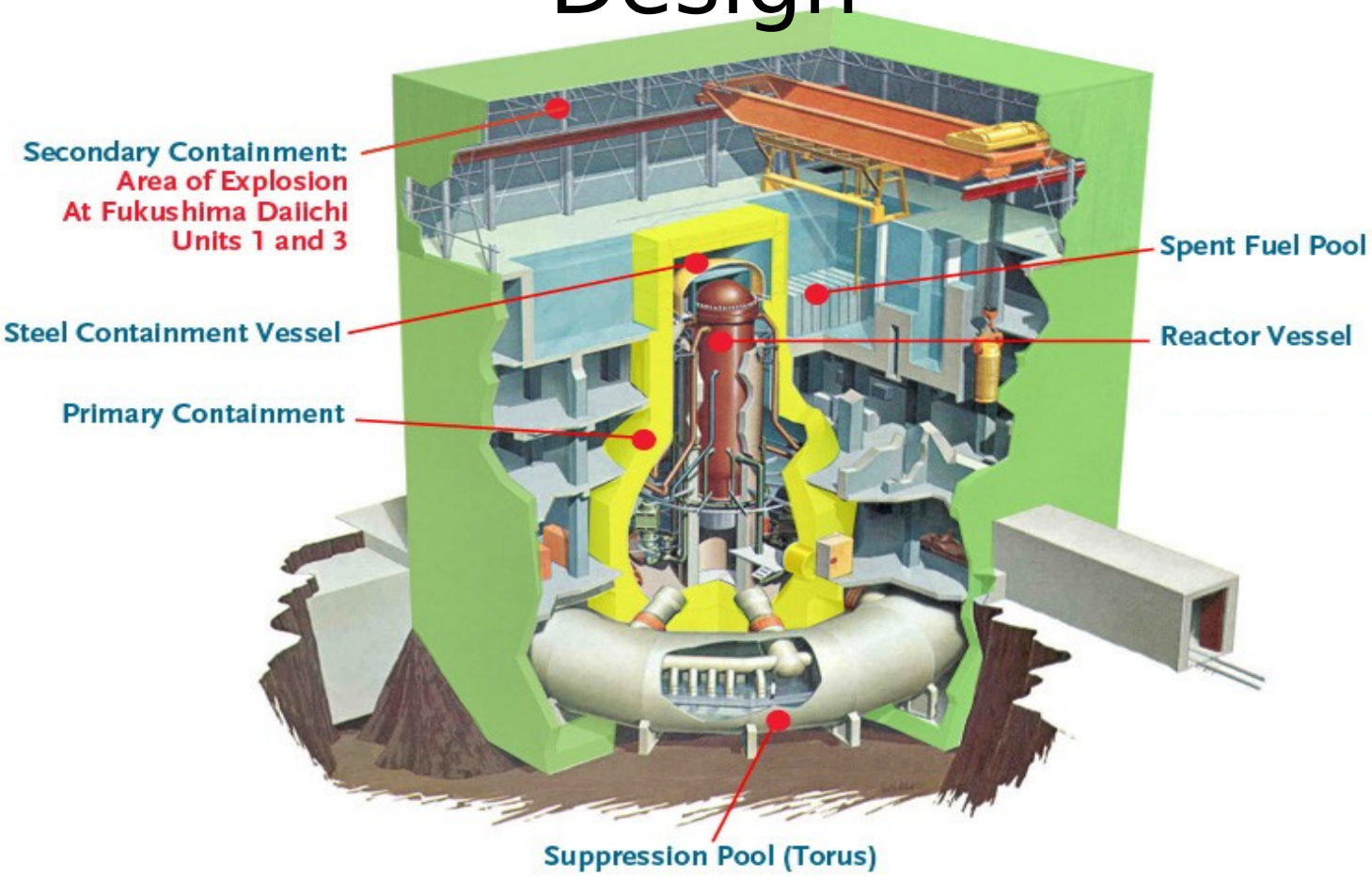
# Industry Changes Resulting from Chernobyl Accident

- RBMK reactors only constructed and operated in Russia and former Soviet Socialist Republics of Ukraine and Lithuania (RBMK reactors could never have been licensed outside of Soviet Union)
- Only changes resulting from Chernobyl accident were modifications to operating RBMK reactors to compensate for design deficiencies that could potentially prompt another accident

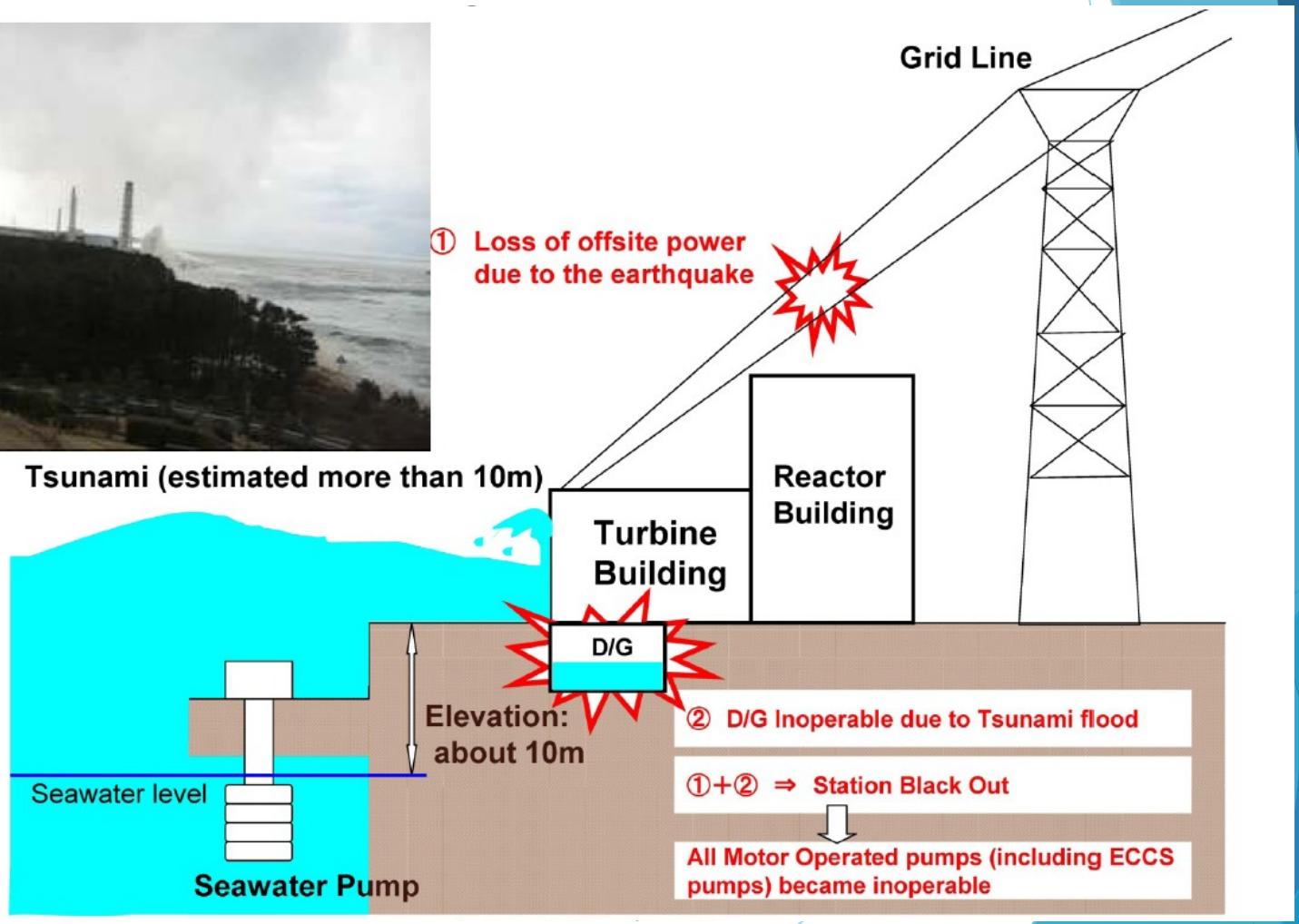
# Fukushima Accident

- Date of accident:  March 11, 2011
- Type of nuclear plant:  4 boiling water reactors with Mark-1 containment buildings
  - Unit 1:  GE BWR-3
  - Unit 2:  GE/Toshiba BWR-4
  - Unit 3:  Toshiba BWR-4
  - Unit 4:  Hitachi BWR-4
- Initiating event:  tsunami that exceeded plant design basis

# Fukushima Units 1-4 BWR Design



# Tsunami Size as Accident Cause


Grid Line
① Loss of offsite power due to the earthquake
Tsunami (estimated more than 10m)
Turbine Building
Reactor Building
D/G
Elevation: about 10m
Seawater level
Seawater Pump
② D/G Inoperable due to Tsunami flood
①+② ⇒ Station Black Out
All Motor Operated pumps (including ECCS pumps) became inoperable

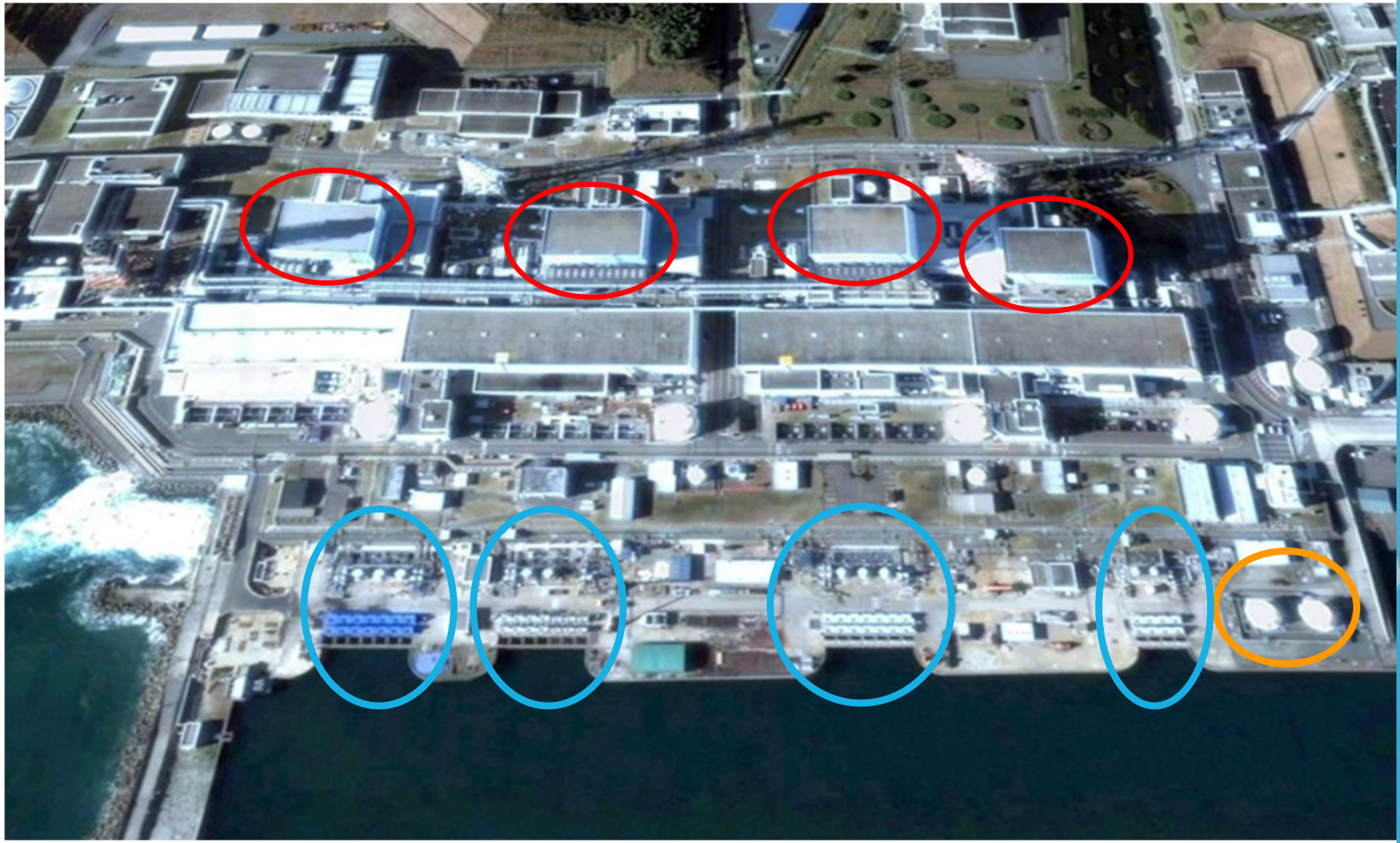
# Fukushima Accident Sequence

- Reactors automatically shut down upon detection of seismic activity
- Earthquake resulted in offsite power transmission line damage
- Emergency diesel generators powered emergency cooling systems
- One hour later, station struck by tsunami that rendered inoperable
  - All multiple sets of emergency diesel generators
  - AC electrical busses
  - DC batteries

# Fukushima Accident Sequence (cont.)

- Tsunami damaged service water systems that provide heat rejection to sea
- Delay cooling caused substantial fuel damage before portable power supplies and pumps brought on-site to re-establish cooling with fresh water and seawater
- Pressure buildup inside reactor containment structures normally relieved by venting; in absence of power, gasses collected at top of reactor buildings
- Hydrogen from fuel cladding oxidation ignited in 3 of 4 reactor buildings

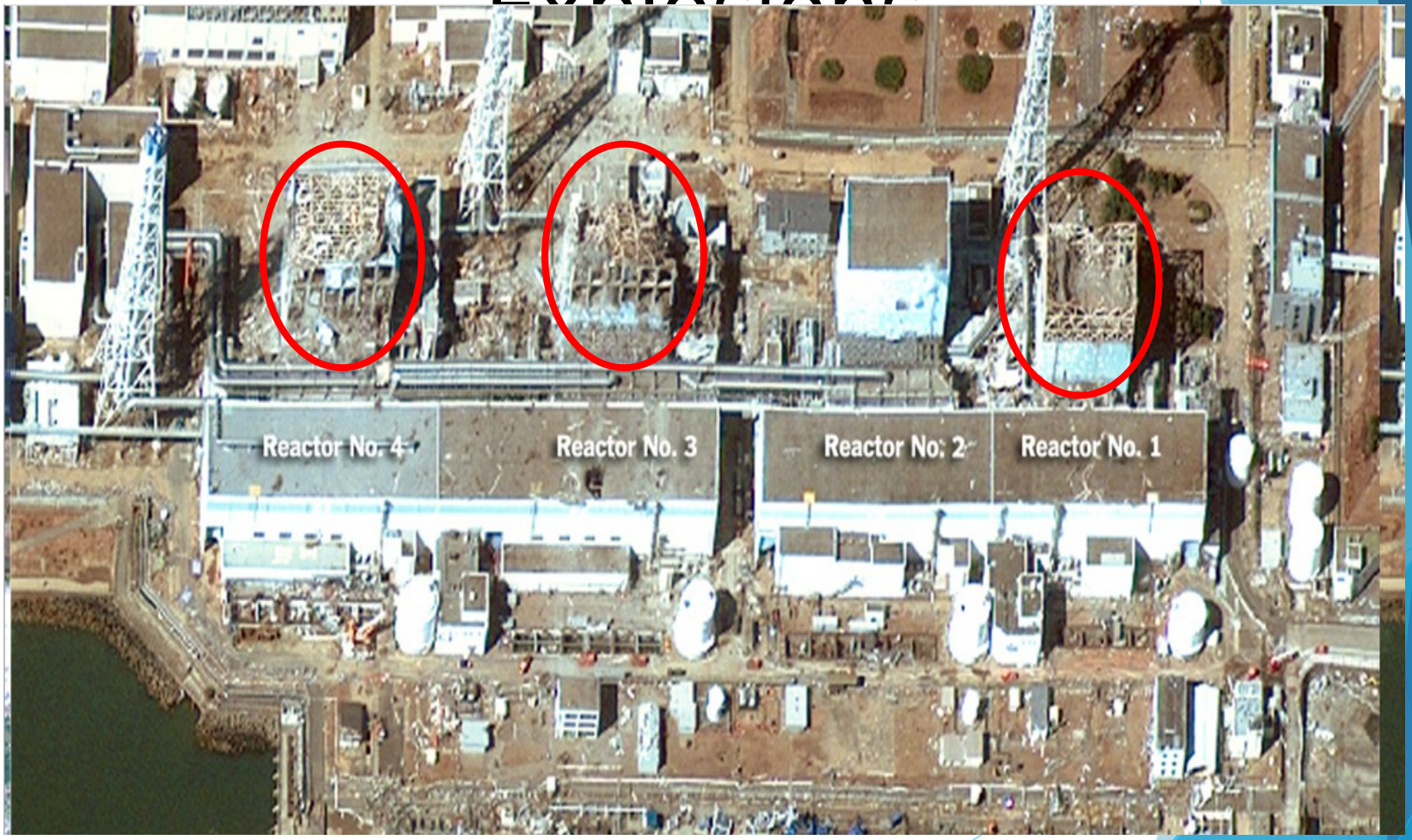
# Fukushima Plant – Before Tsunami



# Fukushima Plant – After Tsunami

# Secondary Containment Bldg. Before and After Hydrogen Explosion

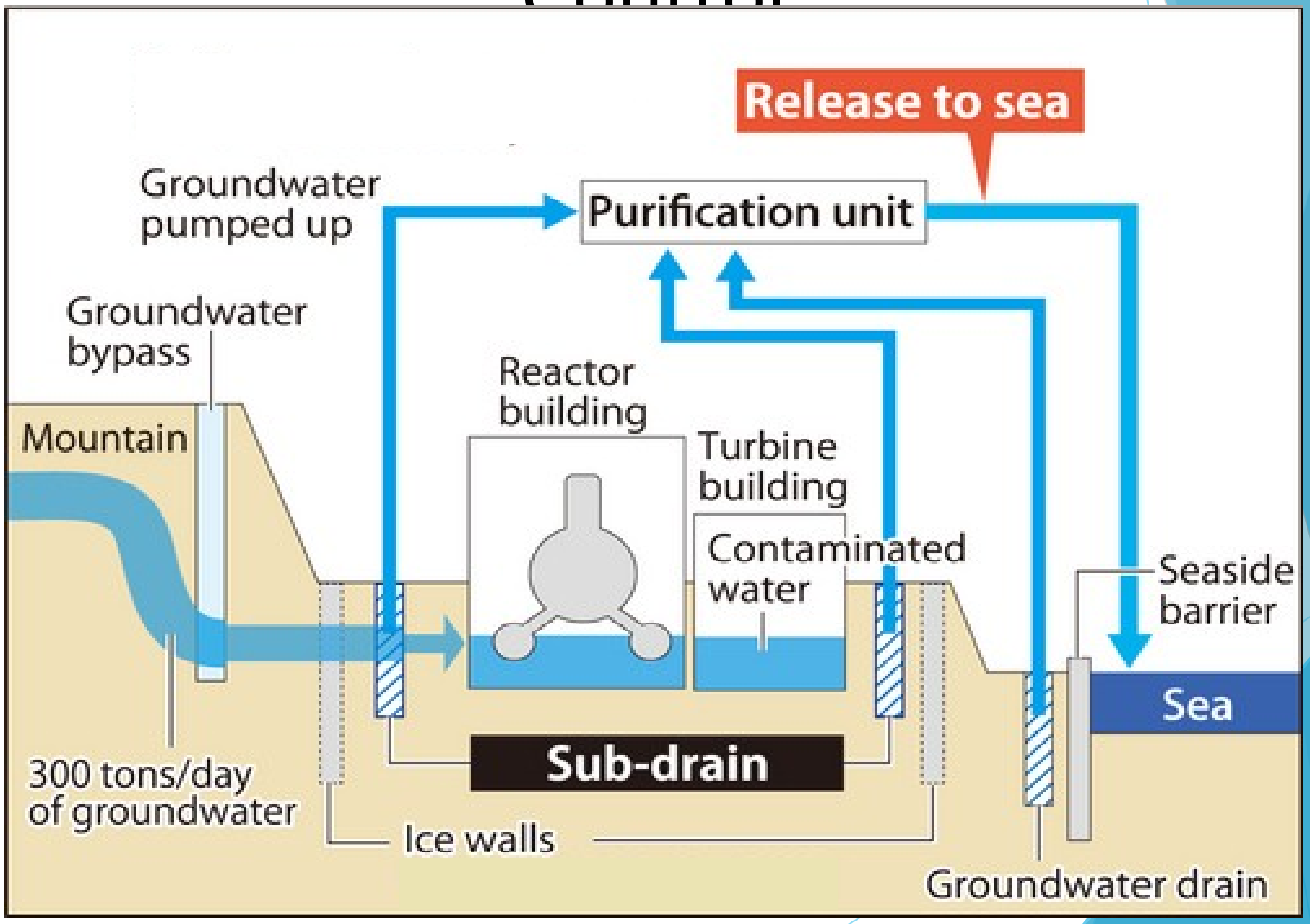
# Fukushima Plant – After $H_2$ Explosions



# Fukushima Accident Radiological Consequences

- No worker thyroid cancer or leukemia cases expected
- No latent cancers expected in workers or local population
- Surrounding land contaminated with relatively low-level radioactive material
- Leakage of radioactively-contaminated water from reactor building basements to sea brought under control by constructing ice walls and drains to collect leakage water for purification

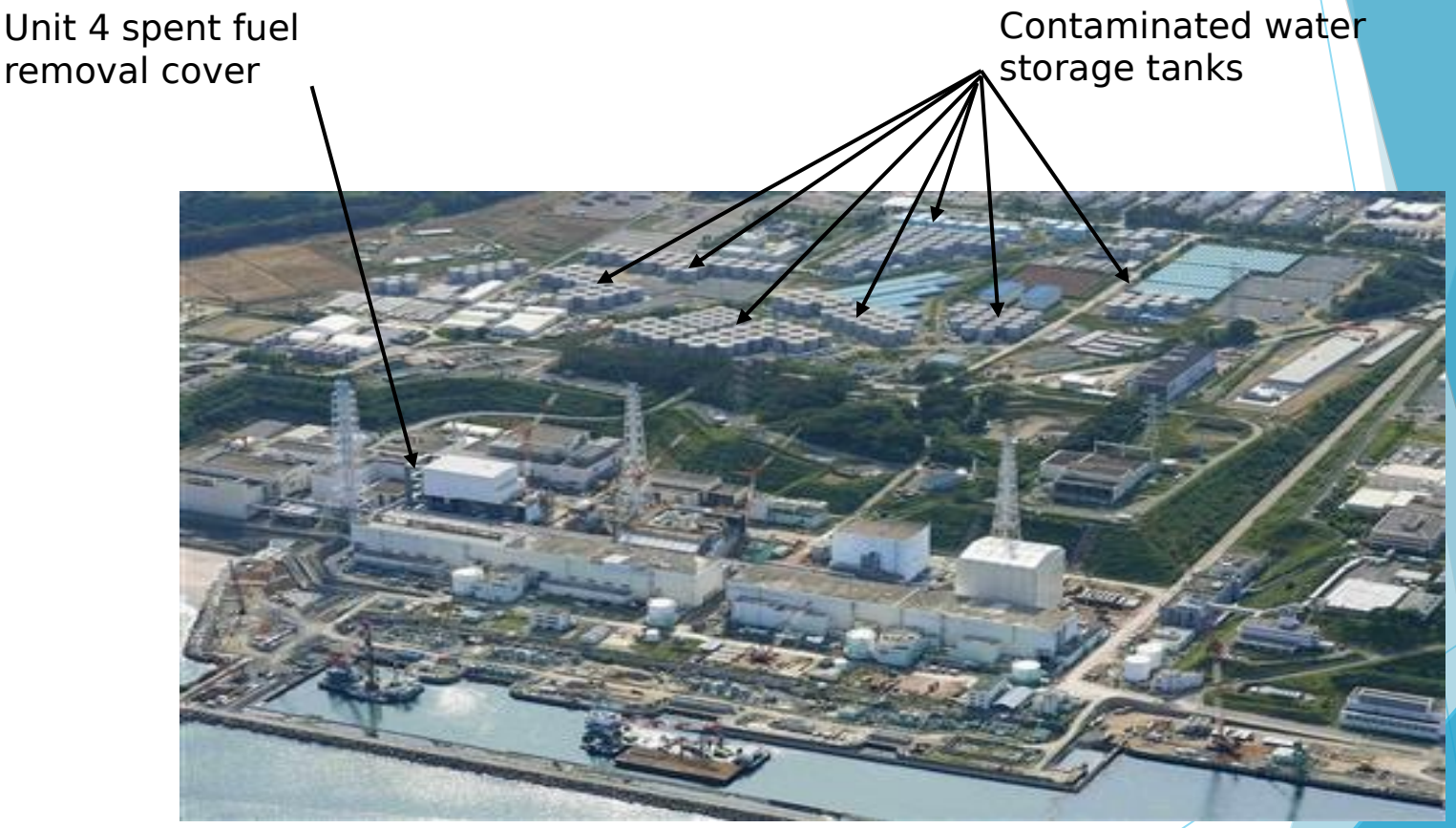
# Fukushima Contaminated Water Control



# Fukushima Current Plant Status

- Recovery activities focused on containment and cleanup of radioactively contaminated material (primarily water and soil)
- All radionuclides in contaminated water storage tanks reduced to levels below legal limits for release, except for tritium
  - Established tritium limits for drinking water, but no established limits for environmental discharges
- Release of tritiated water to Pacific Ocean began in August 2023

# Fukushima Current Plant Status



# Industry Changes Resulting from Fukushima Accident

- 2011 accident at Fukushima-Daiichi plant caused by occurrence of tsunami that exceeded plant design basis
- Following accident, nuclear power industry embarked on significant effort to evaluate effect of beyond-design-basis (BDB) events (particularly earthquakes, tsunamis, and floods) on safety of nuclear power plants

# Beyond-Design-Basis Events

What constitutes beyond-design-basis event

- Event has extremely low probability of occurrence
- Involves successive failures of multiple barriers provided for fission product retention
- Has potential to cause serious reactor core damage, including meltdown
- Has potential for public harm

# Beyond-Design-Basis Event Evaluation

No formalized analysis approach, but evaluation documentation must

- show understanding of BDB event risks and available risk controls,
- assess costs and benefits associated with event risk mitigation,
- assess adequacy of plant's emergency preparedness plan for responding to such events, and
- show understanding of effects of event occurrence on plant safety equipment survivability

# Fukushima – Beyond Design Basis?

- Design basis tsunami set before 1970
  - 5.5 m wave height
- 1971 design basis – plant met all standards, operating license granted
- 14 tsunamis with fatalities since 1895
  - 1896 tsunami had 25 m wave height at origin, and resulted in 22,000 fatalities
- 2005 and 2007 earthquakes shook three reactors with beyond-design-basis ground accelerations

# Occurrence of Low Probability Events

Just because an event has an extremely low probability or frequency, it can still happen today, tomorrow, or next week. In fact, it could occur today, *and* tomorrow, *and* next week. It's not likely, but neither are any other catastrophes that strike without any apparent schedule (e.g., earthquakes, floods, tsunamis, etc.).

# Risk Acceptability

- Quantitative risk assessments generally do not address risk perceptions, or what constitutes “acceptable or tolerable level of risk”
- What constitutes an acceptable level of risk?
  - What individuals or societies are willing to accept or tolerate in exchange for perceived benefits
  - What individuals or societies are willing to accept or tolerate in order to avoid taking undesired mitigation measures or costly protective measures
  - What is the most acceptable or tolerable option in a decision-making activity

# What Have We Learned?

1975 Reactor Safety Study (WASH-1400) concluded that most likely reactor core meltdown accident has modest public consequences – validated by both TMI and Fukushima accidents

- Reactor containment structures effective in minimizing accident radiation releases
- No observed cancer increases prove that LNT model used to predict radiation-induced cancer risk not valid for low-level exposures
- Fallacy of LNT model also revealed by Chernobyl accident; elderly people who returned to Exclusion Zone experienced no adverse health effects from low-level radiation exposures